(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) **International Patent Classification[7]:** G02B 17/08	(72) **Inventor: SHAFER, David, R.**; 56 Drake Lane, Fairfield, CT 06430 (US).
(21) **International Application Number:** PCT/EP00/13257	(81) **Designated States** *(national)*: JP, KR.
(22) **International Filing Date:** 23 December 2000 (23.12.2000)	(84) **Designated States** *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR).
(25) **Filing Language:** English	
(26) **Publication Language:** English	**Published:**
(30) **Priority Data:** 60/176,190 14 January 2000 (14.01.2000) US	— *without international search report and to be republished upon receipt of that report*
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(54) Title: MICROLITHOGRAPHIC REDUCTION PROJECTION CATADIOPTRIC OBJECTIVE
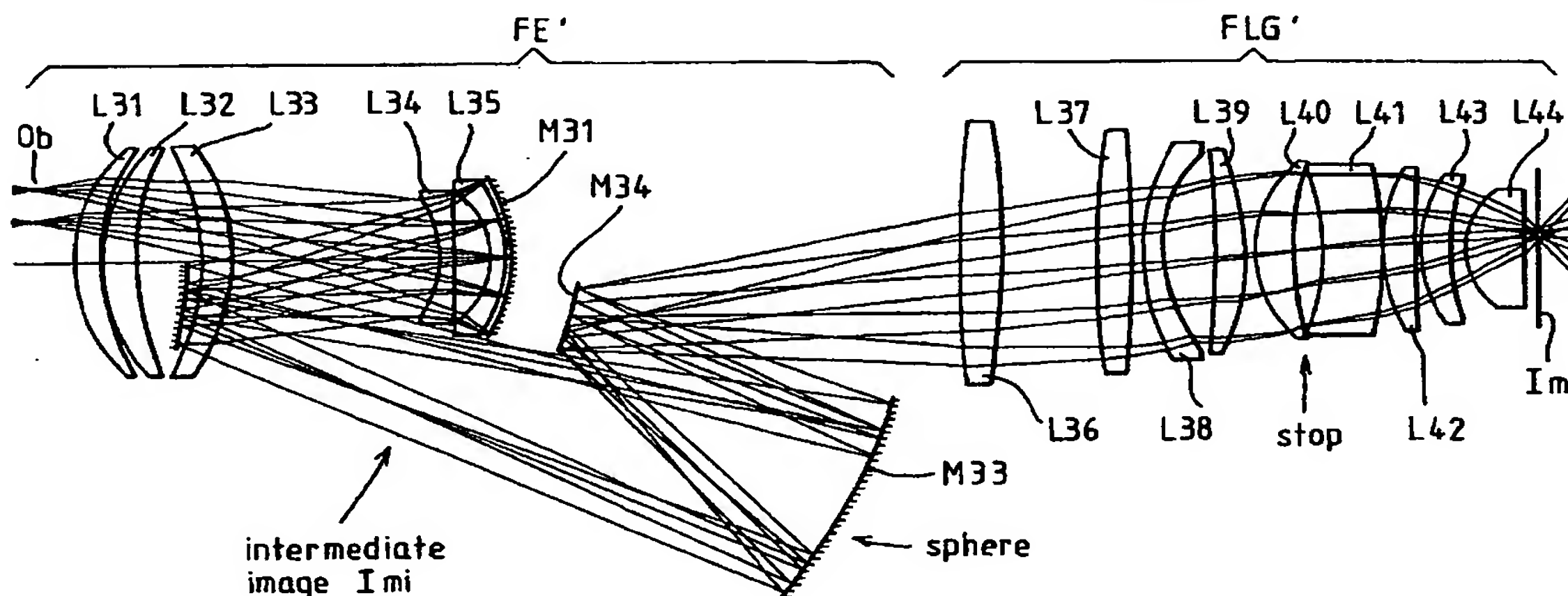
(57) Abstract: Microlithographic reduction projection catadioptric objective, which is devoid of planar folding mirrors and which comprises an aperture plane (stop) on the image side of the most imageward curved mirror (M34). After the most imageward curved mirror (M34) the beam is diverging. The most imageward curved mirror (M34) is convex. The objective consists in sequence from the object side (Ob) to the image side (Im) of a catadioptric group (L31-L35, M31, M32) giving a real intermediate image (Imi), a catoptric or catadioptric group (M33, M34) giving a virtual image, and a dioptric group (FLG') giving a real image.

Microlithographic Reduction Projection Catadioptric Objective

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The invention concerns a microlithographic reduction projection catadioptric objective of a type comprising an even number greater than two of curved mirrors, being devoid of planar folding mirrors and featuring an unobscured aperture.

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Such objectives are known from EP 0 779 528 A (fig. 3) as variants of pure catoptric objectives, with six mirrors and three lenses. All optical surfaces are symmetric to a common axis and object plane and image plane are situated on this axis upstream and downstream of the objective. However, all but one mirrors need to be cut off sections of bodies of revolution, so that mounting

15   and adjustment face difficulties The lenses serve only as correcting elements of minor effect. The most imageward mirror is concave.

US 4,701,035 (fig. 12) shows a similar objective. This one, however, has nine mirrors, two lenses and two intermediate images and object plane and image plane are situated within the

20   envelope of the objective.

In both cases the image field is an off-axis ring sector.

A fully axially symmetric type of catadioptric objective is known form DE 196 39 586 A

25   (US ser. No. 09/263788), e. g., with two opposing concave mirrors, image field centered at the axis and a central obscuration of the aperture.

Another type of catadioptric objectives suitable for microlithographic reduction projection has only one concave mirror, but at least one folding mirror, and is known from US 5,052,763 and

30   EP 0 869 383 A inter alia and is referenced here as "h-design".

US 5 323 263 A gives a microlithographic reduction projection catadioptric objective with multiple folding mirrors, where an intermediate image is arranged subsequent to a first concave mirror and a singly passed lens group.

35

US 5 575 207 A and US 4 685 777 show very similar multiply folded catadioptric objectives.

It is an object of the invention to provide a generic objective of good capabilities of chromatic correction for typical bandwidths of excimer laser light sources, which allows for high imageside

40   numerical aperture, and which reduces complexity of mounting and adjusting.

The solution of this problem is found in the objectives according to the independent claims 1, 2, 4, 6-8 and 10. The dependent claims give advantageous varieties and optimizations of this. Claim 22 gives a projection exposure system incorporating such an objective. All the features of the

45   different claims can be combined in various combinations according to the invention.

The invention is described in detail with respect to the drawing, where

          Fig. 1 shows a front end of an objective,
50   Fig. 2 shows the lens plan of a basic version of the objective, and
          Fig. 3 shows a more sophisticated version.

The basic idea is to replace the front end of an "h-design" objective with a different front end that will give a single axis system.

5   In the simplest version of this new front end, set up to be part of a –0.25 reduction. 0,75 image side NA system with a 7 mm x 26 mm rectangular image field size, the optical elements look like the lens section of Fig. 1. This catadioptric partial system provides a virtual image on the right hand side, which has enough axial chromatic aberration to compensate for a conventional focussing lens group there which forms a 0.75 NA image. A real pupil or aperture plane is formed on the right hand end of the system. The system shown has enough Petzval sum so that
10   the focussing lens group can be made up of mostly positive power lenses.

       One will notice that there is only one field lens L1 in this system, right near the object plane (Ob) end of the system. That location should be an advantage with respect to the lens heating situation. There are no asphercis in this front end, and none are needed. The mirrors M1 to M4
15   are all spherical and coaxial to the common optical axis. It is possible to make this front end system be corrected for spherical aberration of the pupil, but that requires a somewhat larger concave mirror than what is shown here. It can as well be corrected in the focusing lens group and therefore here it was tried to minimize the size of the concave mirror M3. Decreased size of mirror M3 simplifies the mechanical construction of the system. In the example of fig. 1 the
20   concave mirror M3 has an illuminated area that is about 165mm wide in the plane of the drawing and about 500 mm in the orthogonal direction, for a 7 mm x 26 mm image field size.

       The greatest distance of any ray from the common optical axis is 370 mm in this example. This is a lot less than is the case for many designs of the "h-design" type, where the concave mirror
25   thickness and mount thickness must be added in to the sideways ray path distance after the fold mirror, from the axis to the concave mirror. The package envelope of this new design is definitely more attractive.

       More axial chromatic aberration and Petzval curvature can be put in by the front end FE than in
30   the example of fig. 1, by making the negative lens L2 near the concave mirror M1 have more power. A strong lens L2 however, tends to put in too much overcorrected spherical aberration and makes the intermediate image aberrations be too large. So a better version of the design has two concave lenses near the concave mirror.

35   The field lens L1 near the object plane Ob can also be split into two weaker lenses, to help control pupil aberration. Finally, the convex mirror M2 that is near the reticle (Ob) can be split off from the field lens L1 surface and made to be a separate optical element. This then gives a more complicated design, but one capable of better performance.

40   It is possible to make this system meet all of the first-order specs, of a typical microlithographic objective, as well as have correction for Petzval curvature, and axial and lateral color correction, with just positive lenses in the telecentric focusing group TFG. An example is shown in Fig.2, without any other kind of aberration correction. Notice that the lens heating is pretty uniform, as the beam diameter is large on all the lenses L21 to L29.
45

       Fig. 3 shows a further developed example. The front end FE' features a field lens group split into 3 lenses L31 to L33. By their help a good quality telecentricity. Also the focussing lens group FLG' now has more lenses L36 to L44. This focussing lens group FLG' has a few asphercis. There are also some asphercis in the catadioptric front end FE' of the design which simplify
50   correction, though they are not compulsory. The large mirror M33 is still made to be a sphere, as this simplifies production.

Preferred locations of the aspheric surface are near an aperture or pupil plane, namely on mirror M31 or on lenses L34, L35, where the marginal ray height exceeds 80% of the height of the neighbouring aperture, and on the other hand on some distant locations with marginal ray height less than 80% of the height of the next aperture. Examples of the last are surfaces of the field

5   lens group or of the last two lenses next to the image plane Im.

The polychromatic r.m.s. wavefront error value in this design now varies from .05 to 0.13 waves over a 26 X 7 mm field at .75 NA in a 4X design.

10   The catadioptric front end FE' is now a little more complicated than in figs. 1 and 2. The design is both side telecentric and is corrected for pupil aberration and distortion. The working distance is 34 mm on the reticle end (Ob) and 12 mm on the wafer end (Im). The system length is about 1200 mm.

15   The focusing lens group FLG' is almost all positive lenses (except L41), with no strong curves. The very large amount oaf aberration at the intermediate image is because the two concave lenses L31, L35 next to the concave mirror M31 do not have the optimum bending under this aspect.

20   Table I gives a listing of lens data of this embodiment.

Mechanical construction of the lens barrel for this sort of objective is very advantageous when compared with catadioptric systems with folding of the optical axis (as "h-design" etc.). Here, only the mirrors M32 and M33 cannot be full disks. Mirror M33, however can be extended to a

25   full annular body which can be mounted in a rotationally symmetric structure. The barrel has to be cut between the lenses L33 and L36 at la lower side of the drawing of fig. 3 to give passage to the light beam, but generally can be cylindrical. Only mirror M33 has to be positioned outside this cylindrical barrel, but at a very moderate distance.

30   With "h-designs" similar effect needs additional folding. Folding mirrors are generally not desirable, as the cause intensity losses and quality degradation of the light beam, production costs and adjustment work without benefit for image quality.

It is well possible to produce mirror M33 as an annular blank and it can be mounted as this

35   annular part in a cylindrical barrel which is extended in diameter in this area.

It can be easily seen, that concave spherical mirror M33 is the only mirror reaching outside of a cylindrical envelope scribed around all the lenses which has the radius of the lens of the greatest radius. This shows again that this sort of objective is suitable for mounting in a compact

40   cylindrical barrel of high intrinsic rigidity.

The lens material in the given examples is calcium fluoride, fluorspar. Other materials, standing alone or in combinations, may be used, namely at other wavelengths of excimer lasers. Quartz glass, eventually suitably doped, and fluoride crystals are such suitable materials.

45

Four, six and eight or more mirror objective designs known in the field of EUV lithography are generally suitable as starting designs for the front end group of the invention, with the eventual deviation that a virtual image instead of a real image is provide. These embodiments are not limiting the scope of the invention. The claims and their combinations give the whole scope. In

50   addition to the curved mirrors cited in the claims planar folding mirrors may occasionally be entered into the system.

3

COD   11s   Table 1
         Shafer-design .75NA.4x.75mm Obj.-hight
                    RDY   THI   RMD   GLA   CCY   THC   GLC
      > OBJ: INFINITY   34.000000   100   100
         1:      147.23281   21.000000   'CAF-UV'   100   100
         2:      236.79522   1.000000   100   100
            ASP:
            K :   0.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :0.273300E-07   B :0.201130E-11   C :-.871260E-16   D :0.118100E-19
            AC :   100   BC :   100   CC :   100   DC :   100

         3:      145.44401   27.000000   'CAF-UV'   100   100
         4:      224.64885   51.185724   100   100
         5:     -223.00016   25.004072   'CAF-UV'   100   100
         6:     -184.59445   162.666291   100   100
         7:      -97.23630   12.000000   'CAF-UV'   100   100
         8:     -928.69926   24.980383   100   100
         9:      -75.28503   15.000000   'CAF-UV'   100   100
        10:     -116.14787   3.000000   100   100
        11:     -134.28262   -3.000000   REFL   100   100
            ASP:
            K :   0.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :0.474810E-08   B :0.506570E-12   C :-.284590E-17   D :0.934830E-21
            AC :   100   BC :   100   CC :   100   DC :   100

        12:     -116.14787   -15.000000   'CAF-UV'   100   100
        13:      -75.28503   -24.980383   100   100
        14:     -928.69926   -12.000000   'CAF-UV'   100   100
        15:      -97.23630   -162.666291   100   100
        16:     -184.59445   -25.004072   'CAF-UV'   100   100
        17:     -223.00016   -11.195502   100   100
        18:     -363.91714   11.195502   REFL   100   100
            ASP:
            K :   0.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :-.107960E-07   B :0.170830E-13   C :-.328180E-16   D :0.143630E-20
            AC :   100   BC :   100   CC :   100   DC :   100

        19:     -223.00016   25.004072   'CAF-UV'   100   100
        20:     -184.59445   162.666291   100   100
        21:      -96.00000   15.000000   100   100
            ASP:
            K : -1.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :0.000000E+00   B :0.000000E+00   C :0.000000E+00   D :0.000000E+00
            AC :   100   BC :   100   CC :   100   DC :   100

        22:      INFINITY   24.980383   100   100
        23:     -247.00000   67.808099   100   100
            ASP:
            K : -1.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :0.000000E+00   B :0.000000E+00   C :0.000000E+00   D :0.000000E+00
            AC :   100   BC :   100   CC :   100   DC :   100

        24:     -237.00000   266.861281   100   100
            ASP:
            K : -1.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :0.000000E+00   B :0.000000E+00   C :0.000000E+00   D :0.000000E+00
            AC :   100   BC :   100   CC :   100   DC :   100

        25:     -470.62323   -266.861281   REFL   100   100
        26:     -210.84570   266.861281   REFL   100   100
            ASP:
            K :   0.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :-.419940E-08   B :-.904030E-13   C :-.297400E-17   D :-.106340E-21
            AC :   100   BC :   100   CC :   100   DC :   100

        27:      INFINITY   35.031723   100   100
        28:     1621.80000   33.000000   'CAF-UV'   100   100
            ASP:
            K :   0.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :0.155580E-07   B :-.854090E-12   C :0.123240E-16   D :-.559700E-21
            AC :   100   BC :   100   CC :   100   DC :   100

        29:     -747.60113   67.859320   100   100
        30:      827.21786   27.000000   'CAF-UV'   100   100
        31:    -1939.50000   20.227637   100   100
        32:      197.25357   14.999969   'CAF-UV'   100   100
        33:      128.31113   39.542169   100   100.
        34:    -1370.10000   24.000000   'CAF-UV'   100   100
            ASP:
            K :   0.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100
            A :-.164770E-07   B :0.155510E-11   C :-.542070E-16   D :0.556740E-20
            AC :   100   BC :   100   CC :   100   DC :   100

        35:     -253.41246   18.476467   100   100
        36:      109.90063   30.001392   'CAF-UV'   100   100
       STO: 242.23740   22.529315   100   100
        38:     -264.99438   46.219742   'CAF-UV'   100   100
        39:     -372.29467   0.998929   100   100
        40:      173.30822   24.000000   'CAF-UV'   100   100
            ASP:
            K :   0.000000   KC :   100
            IC :   YES   CUF: 0.000000   CCF: 100

                                        4

```
      A  :..28520E-07    B  :-.915530E-11   C  :-.62804DE-15   D  :-.946..vE-19
      AC :    100        BC :     100        CC :     100       DC :     100

  41:     1411.60000          4.845900                          100    100
  42:      110.28842         22.740804      'CAF-UV'            100    100
  43:      160.79657         13.371732          .               100    100
  44:       69.10873         45.185600      'CAF-UV'            100    100
  45:     -895.78799         11.999039                          100    100
      ASP:
      K  :   0.000000    KC :     100
      IC :     YES       CUF:   0.000000    CCF:     100
      A  :-.113590E-06   B  :0.281520E-09   C  :-.171880E-12   D  :0.507740E-16
      AC :    100        BC :     100        CC :     100       DC :     100

  IMG:      INFINITY          0.000000                          100    100
```

```
SPECIFICATION DATA
   NAO      -0.18750
   TEL
   DIM        MM
   WL       157.63       157.63      157.63
   REF         2
   WTW         1            1           1
   XOB       0.00000      0.00000     0.00000     0.00000     0.00000
             0.00000      0.00000
   YOB       0.00000     26.51700    40.00000    53.03300    64.95100
            70.15600     75.00000
   WTF       0.00000      0.00000     1.00000     1.00000     1.00000
             1.00000      1.00000
   VUX       0.00000     -0.00138    -0.00308    -0.00534    -0.00803
            -0.00941     -0.01082
   VLX       0.00000     -0.00138    -0.00308    -0.00534    -0.00803
            -0.00941     -0.01082
   VUY       0.00000     -0.00065    -0.00224    -0.00398    -0.00520
            -0.00531     -0.00535
   VLY       0.00000     -0.00370    -0.00706    -0.01156    -0.01709
            -0.01985     -0.02220
```

```
APERTURE DATA/EDGE DEFINITIONS
   CA
          APERTURE data not specified for surface Obj thru  46

PRIVATE CATALOG
   PWL         157.63       157.63      157.63
   'CAF-UV'   1.558411     1.558410    1.558409

REFRACTIVE INDICES
   GLASS CODE              157.63       157.63      157.63
   'CAF-UV'               1.558409     1.558410    1.558411
```

No solves defined in system

No pickups defined in system

```
INFINITE CONJUGATES
   EFL    -66053.1391
   BFL    -16500.9052
   FFL     0.2642E+06
   FND       0.0000
AT USED CONJUGATES
   RED      -0.2500
   FNO      -0.6667
   OBJ DIS  34.0000
   TT     1198.5356
   IMG DIS  11.9990
   OAL    1152.5365
   PARAXIAL IMAGE
   HT       18.7496
   THI      12.0008
   ANG       0.0000
   ENTRANCE PUPIL
   DIA     0.3818E+10
   THI     0.1000E+11
   EXIT PUPIL
   DIA     25217.8299
   THI    -16501.3415
CODE V> out t
```

5

Claims:

1. Microlithographic reduction projection catadioptric objective devoid of planar folding mirrors and comprising an aperture plane on the image side of the most imageward curved mirror.

2. Microlithographic reduction projection catadioptric objective, characterized in that after the most imageward mirror curved the beam is diverging.

3. Microlithographic reduction projection catadioptric objective, according to claim 1 characterized in that it consists of 4 curved mirrors and more than 8 lenses.

4. Microlithographic reduction projection catadioptric objective, characterized in that it is system with an unobscured pupil comprising a straight axis of symmetry of all the curvatures of all optical elements, where no more than two optical elements are cut to deviate substantially from disk from.

5. Microlithographic reduction projection catadioptric objective, according to claim 3 comprising no more than one optical element which is cut in a substantially non rotationally symmetric form.

6. Microlithographic reduction projection catadioptric objective consisting in sequence from the object side to the image side of a catadioptric group giving a real intermediate image, a catoptric or catadioptric group giving a virtual image, and a dioptric group giving a real image.

7. Microlithographic reduction projection catadioptric objective comprising in sequence from the object side to the image side a field lens group, a catadioptric group comprising one or more negative lenses and a concave mirror, generating axial chromatic aberration, a group comprising an odd number of curved mirrors, and an positive lens group.

8. Microlithographic reduction projection catadioptric objective comprising in sequence from the object side to the image side a catadioptric group comprising one curved mirror and having a negative reduction ratio, a group comprising an odd number of curved mirrors and having a positive reduction ratio, and a dioptric lens group having a negative reduction ratio.

9. Objective according to claim 6, wherein the catadioptric group comprises a positive field lens group and a negative lens group next to the mirror, and wherein the dioptric lens group comprises more positive than negative lenses.

10. Microlithographic reduction projection catadioptric objective, characterized in that the most imageward curved mirror is convex.

11. Objective according to a combination of at least two of the preceding claims.

12. Objective according to at least one of the preceding claims, comprising a straight axis of symmetry of all the curvatures of all the optical elements.

13. Objective according to at least one of the preceding claims, comprising an intermediate image, with at least two curved mirrors being arranged upstream in the beam path.

6

14. Objective according to at least one of the preceding claims, characterized in that the image side numerical aperture is NA = 0.7 or greater, at an image field of 5 mm x 20 mm to 8 mm x 30 mm.

5   15. Objective according to at least one of the preceding claims, characterized in that all lenses when built in as full disks do not obstruct the beam path.

16. Objective according to at least one of the preceding claims comprising at least one spherical mirror.

10

17. Objective according to at least one of the preceding claims, the optical surfaces of the curved mirrors being sections of or full surfaces of revolution, all with a common axis.

18. Objective according to at least one of the preceding claims comprising a subsystem with four
15   curved mirrors, where in sequence from the object plane end the first and third curved mirror are concave and the fourth is convex.

19. Objective according to at least one of the preceding claims comprising an aperture plane located within a catadioptric chromatic aberration generating group consisting of at least one
20   negative lens and a concave mirror.

20. Objective according to at least one of the preceding claims comprising a field lens group next to the object plane and being object side telecentric.

25   21. Objective according to at least one of the preceding claims, characterized in that all lenses are located within a cylindrical envelope of minimal radius, where all but one curved mirrors are located within the same envelope.

22. Projection exposure apparatus comprising an excimer light source, an illumination system, a
30   reticle handling, positioning and scanning system, a projection objective according to at least one of the preceding claims, and a wafer handling, positioning and scanning system.
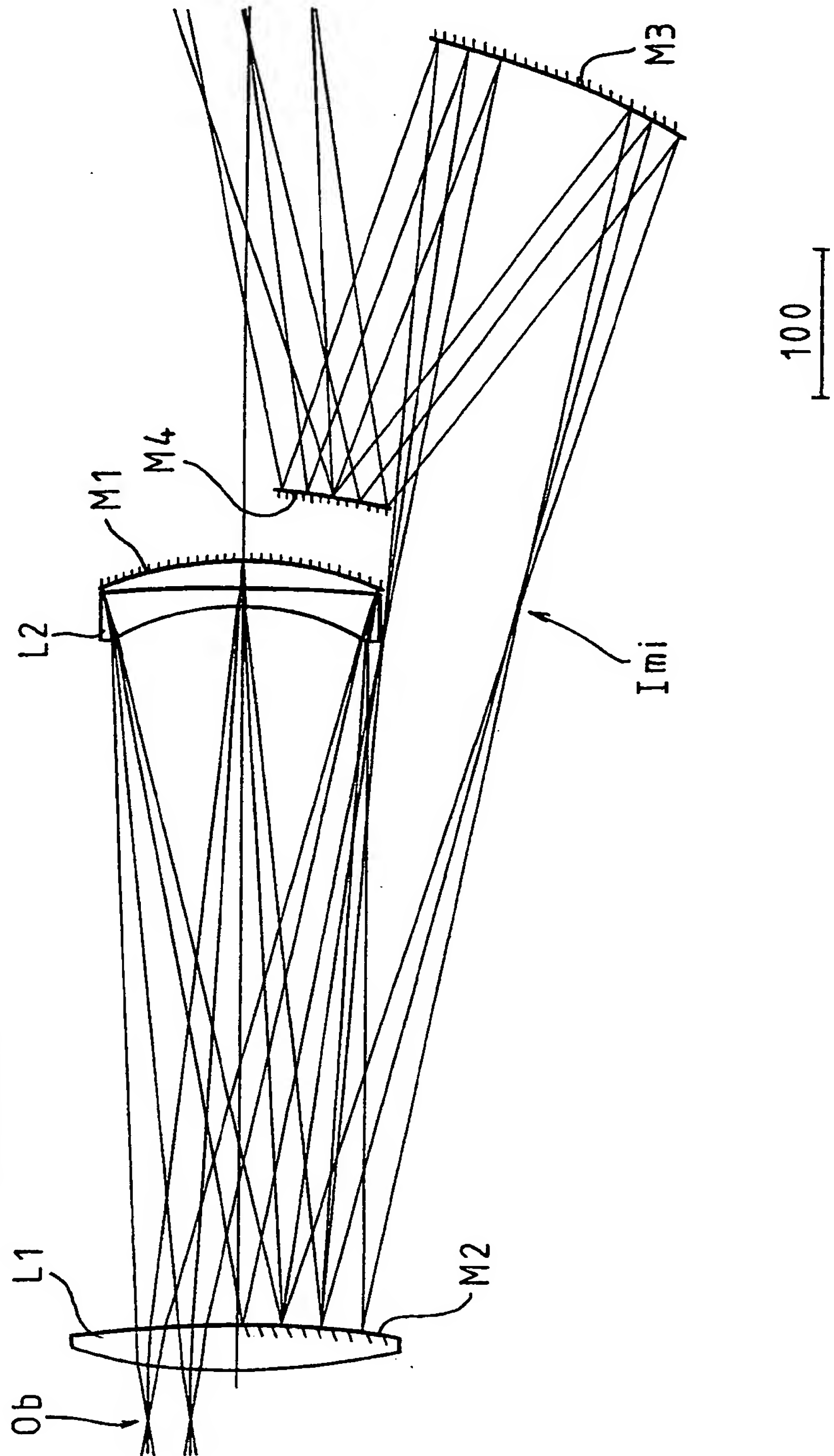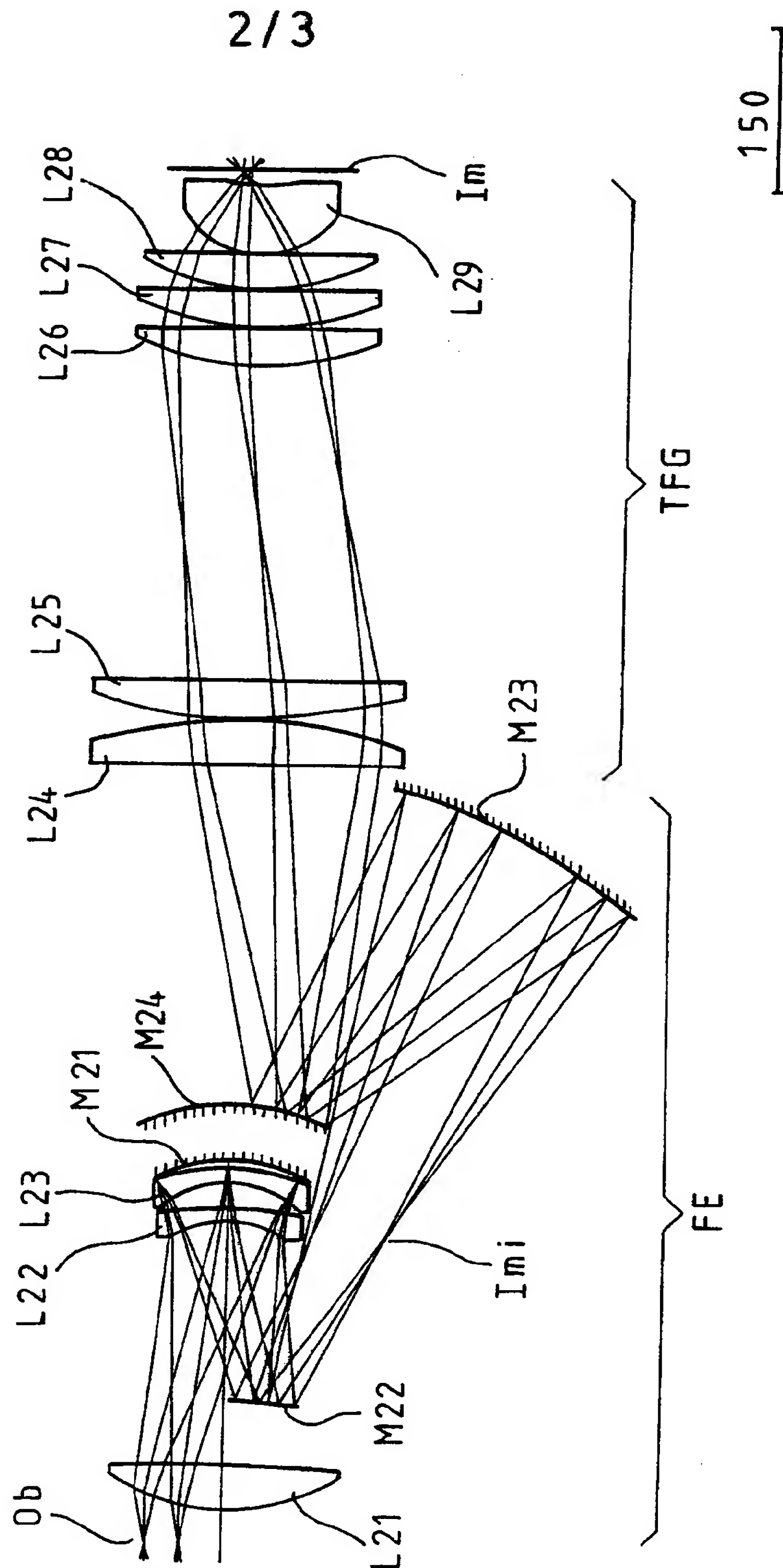
FIG.1

FIG.2

FIG.3